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MODELING CARBON AND NITROGEN BIOGEOCHEMISTRY IN FOREST ECOSYSTEMS

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Abstract: A forest biogeochemical model, Forest-DNDC, was developed to quantify carbon sequestration in and trace gas emissions from forest ecosystems. Forest-DNDC was constructed by integrating two existing models, PnET and DNDC, with several new features including nitrification, forest litter layer, soil freezing and thawing etc, PnET is a forest physiological model predicting forest photosynthesis, respiration, C allocation, and litter production. DNDC is a soil biogeochemical model predicting soil organic matter turnover, trace gas emissions and N leaching. The two models were linked to each other by exchanging information of litter production, plant demand for water and N, and availability of water and N in soil. Input parameters required by Forest-DNDC are daily meteorological data, forest type and age, soil properties, and forest management practices (e. g., harvest, thinning, fire, reforestation, drainage, wetland restoration etc.). For wetland applications, observed or modeled water table data are required to drive the soil redox potential dynamics. Forest-DNDC runs at daily time step, and produces daily and annual results of forest growth, net ecosystem C exchange, fluxes of CO_2, CH_4, N_2O, NO, N_2, and NH_3 emissions, and N leaching from the rooting zone. The modeled C and N fluxes can be compared with the observations gained with static chamber, automated chamber, or Eddy tower facilities. Actually, Forest-DNDC has been tested against measured fluxes of CO_2, CH_4, N_2O, and NO at about 20 forested sites in North America, Europe, and Oceania. Currently, Forest-DNDC is being linked to GIS databases and hydrological models for estimating environmental impacts of forest management in the U. S. and several European countries at regional scale. We also plan to test this integrated simulation system at a dozen research sites across China that were recently instrumented with eddy covariance flux measurements under the US-China Carbon Consortium (USCSS) framework.

Key words: Forest ecosystems, C and N cycles, DNDC, biogeochemical process modeling

Introduction

Forest management practices impact not only forest productivity but also environmental safety. Any change in forest management would simultaneously alter the above- and under-ground biomass components, the forest floor dynamics, and the soil biogeochemistry in the ecosystems. The impacts could vary highly in space and time due to the variations in the climate, soil and vegetation conditions. Both wetland and upland forests play an important role in the carbon (C) sequestration, trace gas emission, and nitrate leaching in terrestrial ecosystems. Forested wetlands are a critical component of forested landscapes, which typically exhibit long-term soil C losses from harvesting and site preparation (Trettin *et al.*, 1995). Demands for better understanding the comprehensive impacts of forest management on forest production, C sequestration, trace gas emission, and nitrate leaching are increasing. During the last seven years, a joint effort between the U. S. and German researchers was made to develop a process-based model of forest C and N biogeochemistry. This paper reports development and applications of the model.

Approach

The core of Forest-DNDC was constructed by integrating PnET, a forest physiological model developed by Aber *et al.* (1996), with DNDC, a soil biogeochemical model (Li *et al.*, 1992, 1994). The integration created a new modeling framework to meet some gaps existing in most forest models in terms of the linkage between forest and soil processes. PnET simulates forest physiological processes but with includes a very limited representation of soil processes. DNDC possesses detailed soil biogeochemical functions but lacks detailed vegetation processes. The integration of PnET with DNDC allows the two models to exchange information at a daily time step. PnET predicts forest growth, litter production, water and N demands; and DNDC receives litter input and tracks its turnover in the soils. In addition, several new features were developed to enhance the forest-soil integration. The new features include detailed nitrification processes, soil freezing and thawing, the forest litter layer, and soil anaerobic biogeochemistry. For example, to simulate C and N dynamics in wetland ecosystems, we added several new algorithms including (1) division of soil profile by ground water table depth, (2) soil Eh evolution, (3) SOC turnover under anaerobic conditions, (4) methane production/consumption, and (5) wetland management practices (e. g., drainage, restoration etc.). Three approaches were built in Forest-DNDC to utilize water table data to drive biogeochemical simulations. The water table data can be obtained from field observations, empirical model simulations, or hydrological model simulations. The integration substantially improved our ability in modeling C and N cycles in forest ecosystems (Li *et al.*, 2000; Stange *et al.*, 2000; Zhang *et al.*, 2002; Cui *et al.*, 2004; Li *et al.*, 2004).

The Forest-DNDC model consists of two components. The first component consisting of soil climate, forest growth and decomposition sub-models predicts forest carbon production, carbon allocation, litter incorporation, soil temperature/moisture/Eh profiles, and soil organic matter decomposition. The second component consisting of nitrification, denitrification and fermentation sub-models simulates C and N transformation driven by the soil microbial activities, which are responsible for production and consumption of methane (CH_4), nitrous oxide (N_2O), nitric oxide (NO) and other trace gases in the soils. The forest growth sub-model simulates photosynthesis, respiration, C allocation and litter production driven by solar radiation, temperature and canopy N content. The soil process sub-models (e. g., decomposition, nitrification, denitrification, fermentation etc.) predict C and N dynamics in forest soils including the forest floor and the mineral soil profile. Major management practices, such as deforestation, reforestation, thinning, burning, drainage, wetland restoration, fertilization etc., have been parameterized and linked to the plant-soil processes. Equipped with these functions, Forest-DNDC is capable of simulating C and N cycles for both wetland and upland forest ecosystems (Fig. 1).

This modeling effort attracted a wide range of interests from researchers worldwide. Through the international collaborations, Forest-DNDC has been tested against 21 forest sites with eddy tower-observed net ecosystem exchange of CO_2 (NEE) fluxes, 28 forest sites with N_2O and NO fluxes, 2 forest sites with CH_4 fluxes, and one site with soil respiration fluxes. Fig. 2, 3 and 4 show comparisons of observed and modeled NEE fluxes from several selected forest sites in the US, Canada, Germany, France and Scotland. Fig. 5 shows observed and modeled soil autotrophic and heterotrophic respirations in a forested wetland in Finland. The capacity of Forest-DNDC in modeling trace gas emissions are shown in Fig. 6 for CH_4 fluxes and Fig. 7 for N_2O fluxes. The results indicate that Forest-DNDC is capable of estimating major C and N fluxes in both upland and wetland forest ecosystems across climate zones, forest types, soil properties and management regimes.

Forest-DNDC is currently employed in several EU forest projects for predicting C sequestration and N gas emissions at regional scale (Butterbach-Bahl *et al.*, 2004; Kiese *et al.*, 2004). In the U. S., Forest-DNDC is being linked to a hydrological model, MIKE SHE, for predicting impacts of forest management on C sequestration, trace gas emissions and N leaching at watershed scale. A watershed at Santee, South Carolina has been selected as a target domain for the up-scaling practices including (1) linking MIKE SHE with Forest-DNDC, (2) comparing modeled results with observations on the water flow, ground water N concentration, stream N loading, soil C dynamics, and forest growth measured at site scale within the Santee watershed; and (3) conducting watershed-scale simulations with alternative management scenarios for predicting their impacts on C sequestration, trace gas emissions, and N leaching.

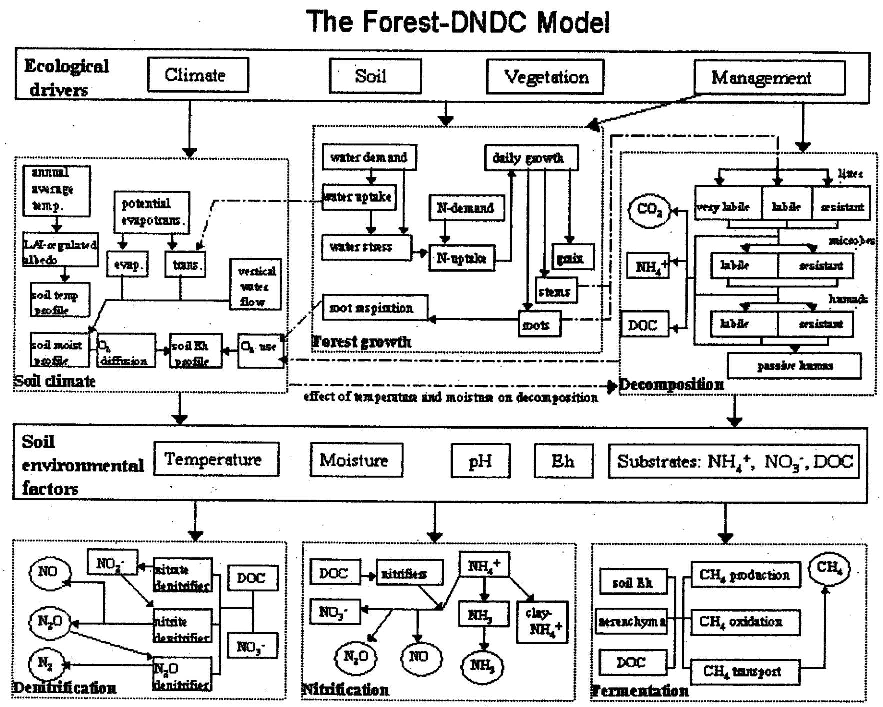

Fig. 1. Structure of the Forest-DNDC model.

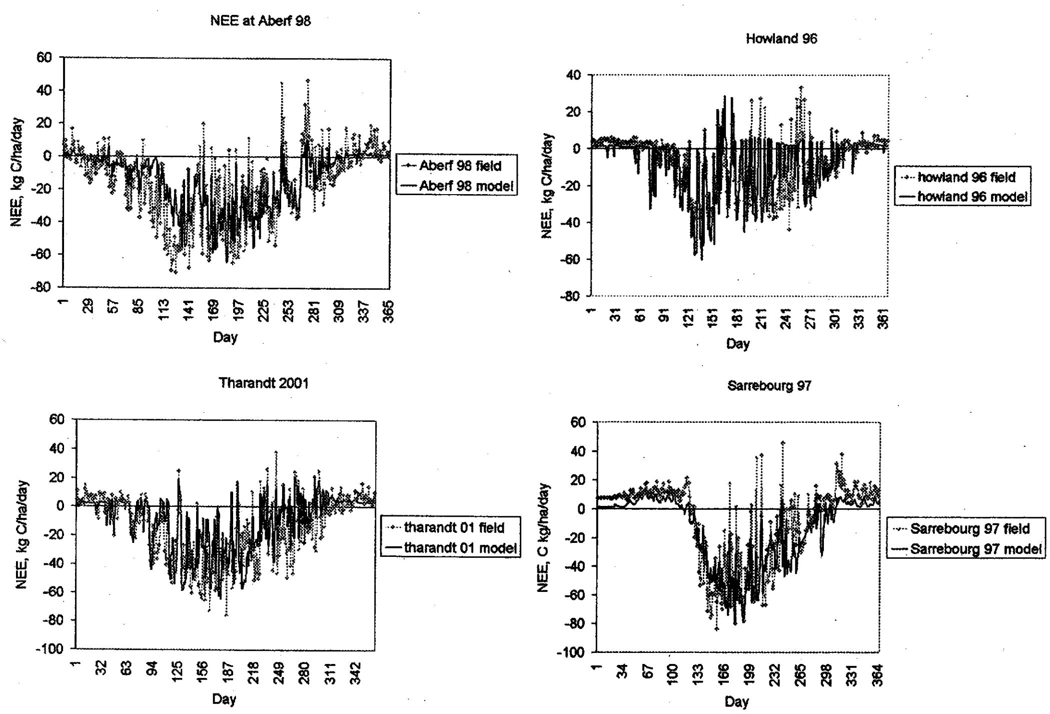

Fig. 2. Forest-DNDC has been validated against twenty one field data sets of tower-observed daily NEE fluxes worldwide. Among the tested cases, four comparisons are shown in this figure. The four cases are Howland Forest (US), Aberfeldy (Scotland), Sarrebourg (France) and Tharandt (Germany). Data source: EU forest GHG project NOFRETETE (2001–2005), in which Forest-DNDC is employed as a central model.

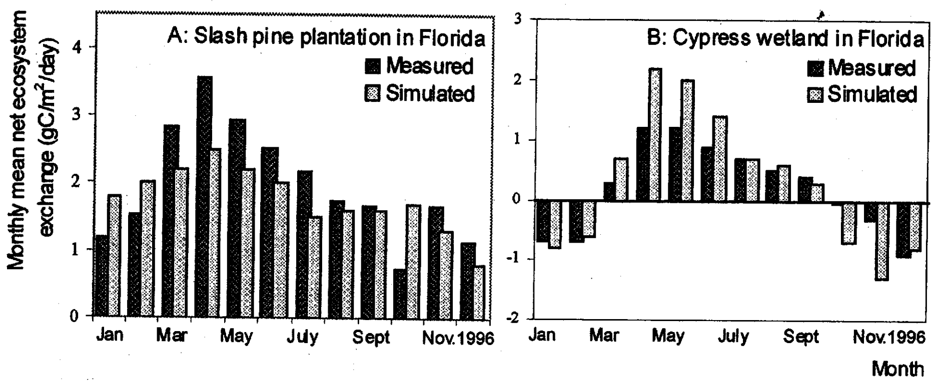

Fig. 3. Ecosystem carbon exchange was simulated with Forest-DNDC for a upland forest (slash pine) and a wetland forest (cypress) in Florida. The modeled results are in agreement with observations. QUESTION: IS CH_4 EMISSION INCLUDED IN THE C-EXCHANGE?

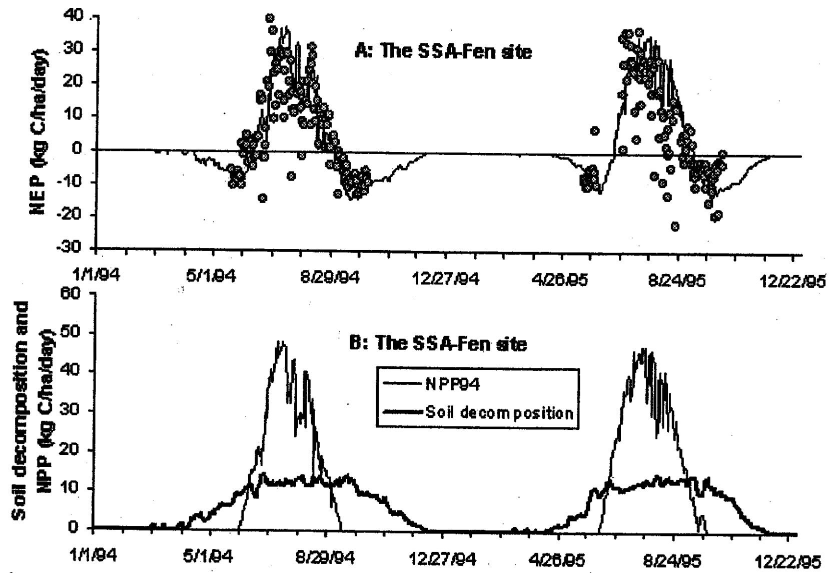

Fig. 4. Forest-DNDC simulated forest NPP and soil heterotrophic respiration for a minerotrophic fen near Alberta, Canada . The modeled ecosystem carbon exchange fluxes are in agreement with observations.

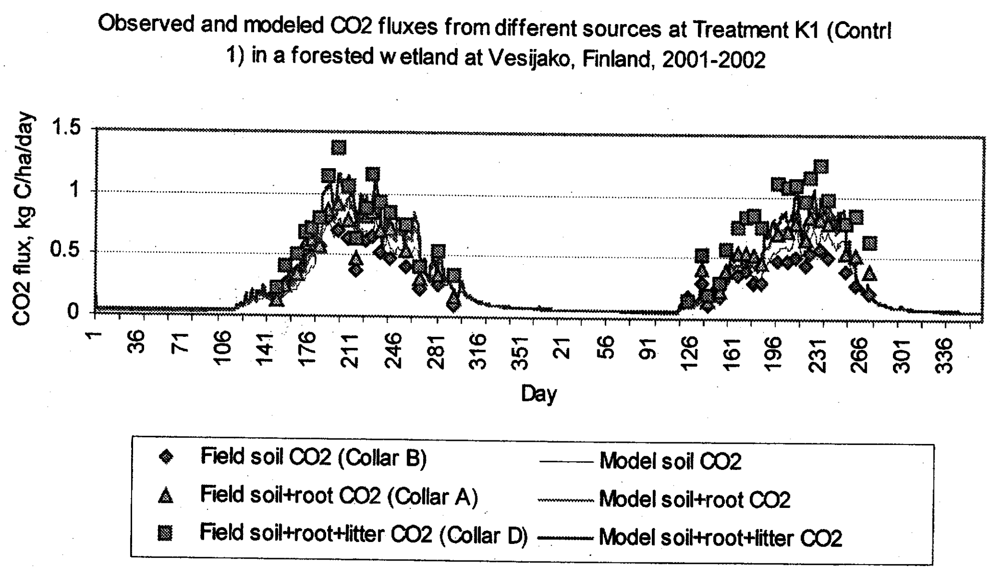

Fig. 5. Comparison between observed and ForestDNDC-modeled soil CO_2 fluxes from a forested wetland at Vesijako, Finland.

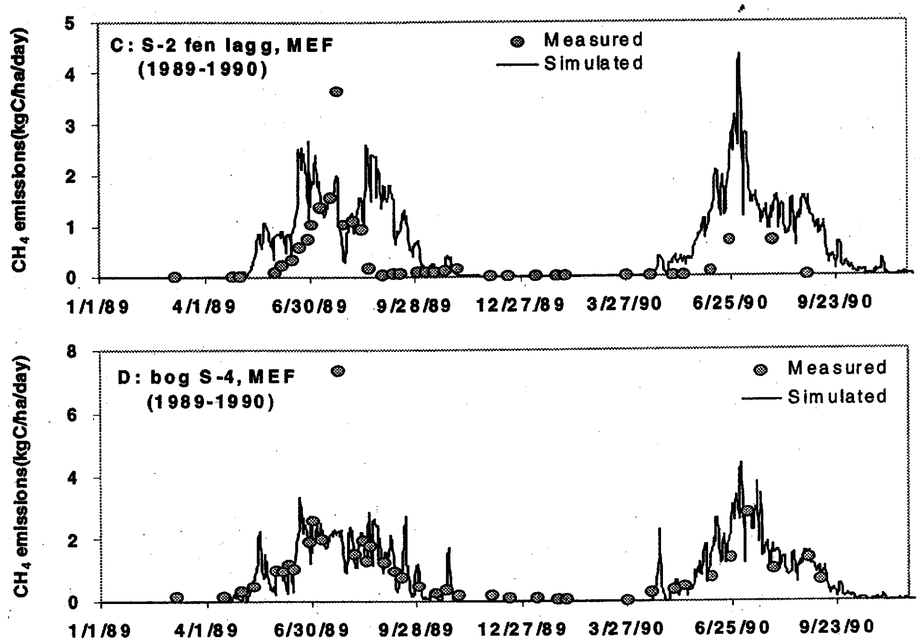

Fig. 6. Comparison of ForestDNDC-modeled CH_4 fluxes with observations for forested wetlands in Minnesota.

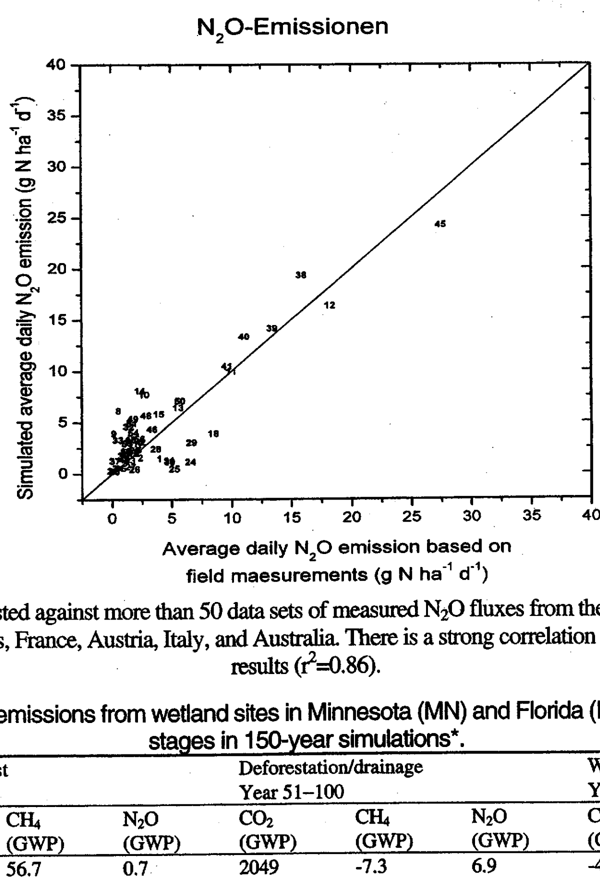

Fig. 7. Forest-DNDC has been tested against more than 50 data sets of measured N_2O fluxes from the forest stands in the US, Germany, Finland, Scotland, the Netherlands, France, Austria, Italy, and Australia. There is a strong correlation between the modeled and observed results (r^2=0.86).

Table 1. Modeled greenhouse emissions from wetland sites in Minnesota (MN) and Florida (FL) during different management stages in 150-year simulations*.

Management stage	Wetland forest Year 1–50			Deforestation/drainage Year 51–100			Wetland restoration Year 101–150		
Greenhouse gas	CO_2 (GWP)	CH_4 (GWP)	N_2O (GWP)	CO_2 (GWP)	CH_4 (GWP)	N_2O (GWP)	CO_2 (GWP)	CH_4 (GWP)	N_2O (GWP)
MN site	-1076 (-3945)	56.7 (1587)	0.7 (358)	2049 (7514)	-7.3 (-204)	6.9 (3373)	-444 (-1628)	40.9 (1146)	0.01 (3)
Net GWP		-2001		10684			-479		
FL site	-4260 (-15620)	784.8 (21974)	0.6 (270)	5450 (19982)	-14.7 (-412)	5.3 (2587)	-2647 (-9707)	676 (18939)	0.00 (1)
Net GWP	6623			22157			9233		

* Units for average annual CO_2, CH_4, N_2O and GWP fluxes are kg C/ha, kg C/ha, kg N/ha and kg CO_2 emission equivalent/ha per year, respectively.

Applications

Forest-DNDC has been used to test impacts of management alternatives on C sequestration and trace gas emissions for two forested wetlands in the U. S. A 150-year management scenario consisting of three stages of wetland forest, deforestation/drainage, and wetland restoration was simulated with Forest-DNDC for two wetlands in Minnesota and Florida. The impacts of the management scenarios on C ecosystem exchange, methane emission, and nitrous oxide emission were quantified and assessed. The modeled results are listed in Table 1. The results suggested that: 1) the same management scenario may produce very different consequences on global warming because of contrasting climatic conditions; and 2) methane and nitrous oxide fluxes played non-negligible roles in mitigation in comparison with carbon sequestration.

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